Spectral Signature of Cosmological Infall Around the First Quasars

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The massive galaxies hosting the earliest supermassive black holes only a billion years after the big bang are expected to be surrounded by a large volume of infalling gas. This infall is halted at the boundary of the host galactic halo by a shock. Here we show that this generic infall pattern imprints a unique signature on the Lyα emission-line profile of bright high-redshift quasars. Absorption by the infalling hydrogen modifies the intrinsic singly-peaked emission line shape into a doubly-peaked profile. Recent spectra of quasars with redshifts $\gtrsim 5$ show apparent evidence for this predicted shape. This evidence confirms for the first time the idea that the earliest known quasars reside in massive ($\gtrsim 10^{12}$ solar mass) host halos. The inferred mass infall rates are consistent with the expected build-up of the quasar host galaxies over the age of the universe at that early epoch.

The Sloan Digital Sky Survey (SDSS) has recently discovered exceptionally bright quasars[1] with redshifts of up to 6.28. Even if these accreting black holes shine near their maximum (Eddington) luminosity, their observed fluxes can only be produced by billion solar mass black holes. Such massive black holes are thought to form only in the centers of galaxies with mass comparable to our own Galaxy, but such massive galaxies should lie within the rarest, most massive dark matter halos in the universe at those early times[2]. There is no observational evidence to date to confirm the presence of these massive halos.

In the standard cosmological model, the earliest galaxies form within massive dark matter halos which themselves form in the densest regions of the universe. Each such halo should be surrounded by a large volume of gas that responds to the strong gravitational pull and falls towards the massive halo. Such infall has been studied analytically in the spherically-symmetric case[3,4], showing that the gas flows smoothly toward the halo until it hits an accretion shock located near the halo boundary. Three-dimensional hydrodynamic simulations show that the most massive halos in the present-day universe (which correspond to rich clusters of galaxies) should be surrounded by strong, quasi-spherical accretion shocks [5,6]. The accretion shock and the larger region of gas infall have not been thoroughly studied because of the difficulty of directly observing the associated low density gas. Recently, preliminary evidence for the existence of accretion shocks around nearby galaxy clusters has been found based on nonthermal emission from the relativistic electrons accelerated in these shocks[7,8,9].

At high redshift, the great sensitivity of resonant Lyα absorption to low density gas[10] offers the possibility of detecting the infalling unshocked gas. The Lyα absorption due to gas around quasars has been modelled before as part of attempts to measure the flux of the ionizing radiation background[11,12] or the neutral hydrogen fraction[13,14,15] in the intergalactic medium. These models have all assumed that the quasar is surrounded by a uniform expanding universe even though it has been shown[16] that the measured level of the ionizing intensity can be seriously overestimated if infall is neglected. In addition to the increase in the mean gas density due to infall, the gas should also be clumped, with part of the gas falling into dense sheets and filaments while the rest of the intergalactic medium is left with a gas density below the cosmic mean. The resonant Lyα absorption is made up of the separate contributions of gas elements at a variety of overdensities; even if high-density clumps produce complete absorption, photons at wavelengths that resonate with gas in voids are more strongly transmitted, and thus clumping actually increases the mean transmission. Previous studies of the Lyα region have for the most part used oversimplified treatments of gas clumping, although recent papers have considered a more realistic distribution of clumps[17,18].

Here we model the resonant Lyα absorption of quasars including the effect of infall. For each quasar we consider the history of the formation of its host halo from an initial positive overdensity. For the initial surrounding density profile at high redshift we adopt the typical profile expected around the dense region that collapses to form the halo[16]. We calculate gas infall down to the radius of the accretion shock, and neglect any Lyα absorption due to the post-shock gas. The hot ($\gtrsim 10^7$K) post-shock gas should be fully-ionized by collisions. Part of it is expected to subsequently cool and collapse onto the galactic disk, although Compton heating by the quasar should keep the virialized gas hotter than $\sim 10^6$K. Even if a thin cold shell of shocked gas remains, it will not change the basic pattern produced by infalling gas since the post-shock gas no longer has a high infall velocity. We set the accretion shock radius to 1.15 times the halo boundary based on an analytic infall solution[4], but our results are not altered substantially as long as the shock radius is indeed close to the virial radius. For the distribution of gas clumps we adopt an analytical fit to numerical simulations[19]. We assume that the clumps are optically thin, and find the neutral fraction separately for each clumping density based on ionization equilibrium with the quasar ionizing flux. We then calculate the mean Lyα transmission averaged over the clump distribution.

In order to predict the Lyα absorption around a quasar we must estimate the mass of its host halo. A tight correlation has been measured in local galaxies between the mass of the central black hole and the bulge velocity dispersion[20,21]. This relation also fits all existing data on the luminosity function of high-redshift quasars within a simple model[22] in which quasar emission is assumed to be triggered by mergers during hierarchical galaxy formation. We use the best-fit[20,21,22] relation, in which the black hole mass in units of $10^8 M_\odot$ (M_8) is related to the circular velocity at the halo boundary in units of 300 km s^{-1} (V_{300}) by $M_8 = 1.5(V_{300})^5$. For the typical quasar continuum spectrum, we adopt a power-law shape of $F_\nu \propto \nu^{-0.44}$ in the rest-frame range 1190–5000Å based on the SDSS composite spectrum[23], and $F_\nu \propto \nu^{-1.57}$ at 500–1190Å using the composite quasar spectrum from the *Hubble Space Telescope*[24]. Based on observations in soft X-rays[25], we extend this power-law towards short wavelengths.

We assume that an active quasar shines at its Eddington luminosity, and we note that for the SDSS composite spectrum[23], the total luminosity above 1190Å equals 1.6 times the total continuum luminosity at 1190–5000Å. Thus, ionizing photons stream out of the quasar's galactic host at the rate $\dot{N} = 1.04 \times 10^{56} M_8$ s^{-1}. We infer the black hole mass using the observed continuum at 1350Å, with the conversion $F_\nu = 1.74 \times 10^{30} M_8$ erg s^{-1} Hz^{-1}. Given that helium is doubly-ionized by the quasar, the frequency-averaged photoionization cross-section of hydrogen is for our template spectrum $\bar{\sigma}_H = 2.3 \times 10^{-18}$ cm^2. The double ionization of helium increases the recombination rate due to the extra electrons, and also produces a characteristic gas temperature of $\sim 1.5 \times 10^4$ K in regions that had already been reionized by a softer ionizing background[26].

Only a limited number of published spectra are currently available for a clear test of our predictions. First, only the brightest quasars, which reside in the most massive halos, produce strong infall over a large surrounding region. The infalling gas density scales as $(1+z)^3$ and the shock radius scales as $(1+z)^{-1}$, so that the absorption optical depth is $\propto (1+z)^4$ and the absorption feature is much weaker at low redshift. In addition, at lower redshifts a forest of transmission spikes of flux appears on the blue side of the Lyα line, and this can contaminate the generic absorption pattern that we predict since the quasar redshift is often not measured with sufficient precision. Even at high redshifts, measuring the detailed Lyα line profile is possible only in a high resolution spectrum with an extremely high signal-to-noise ratio.

Figure 1 shows two particularly high-quality spectra and compares them with our model predictions. Both spectra show our predicted double-peak pattern and disagree with the single-peaked profile predicted by previous models that ignored infall. In particular, models that assume a pure Hubble flow offer no explanation for the sharp flux drop observed at $\Delta\lambda > 0$ in both spectra. In our model, this flux drop corresponds to the accretion shock, and its observed $\Delta\lambda$ depends on the infall velocity, which is proportional to the halo circular velocity and thus[2] to $M^{1/3}(1+z)^{3/2}$, in terms of the halo mass M and the redshift z. The actual physical distance of the accretion shock in the model is 86 kpc and 80 kpc for the quasars at $z = 4.795$ and $z = 6.28$, respectively. Our model with infall also fits approximately the observed secondary blue peak. This peak corresponds to infalling gas and we do not expect to fit its shape in detail; our model averages over all lines of sight and mass density realizations, but observable random fluctuations around our predicted mean are expected in each specific spectrum. However, the prediction of a second peak rather than a smooth fall-off is generic and insensitive to the detailed model assumptions. At a distance R from the quasar the resonant optical depth depends on $\rho^2 R^2$, where ρ is the density including infall; one factor of ρ comes from the total gas density, the second comes from the H I fraction which increases with ρ due to recombinations, and the R-dependence results from the R^{-2} decline of the ionizing intensity of the quasar. Thus, a second peak should appear as long as infall produces a density profile falling off faster than $1/R$ (our model predicts $R^{-3/2}$) before asymptoting to the cosmic mean value of unity. We note that in our model the position of the blue peak corresponds to gas at $R = 0.45$ Mpc ($z = 4.795$) or 0.41 Mpc ($z = 6.28$).

However, the more distant region where the flux drops toward zero can be modelled much more robustly. In particular, significant flux is observed at $\Delta\lambda = -45$Å ($z = 4.795$) and $\Delta\lambda = -90$Å ($z = 6.28$), respectively. These relatively distant regions are only weakly affected by infall and the observed positions translate to a distance from the quasar of 3.8 Mpc ($z = 4.795$) or 4.2 Mpc ($z = 6.28$). In models that do not include a clump distribution, the optical depth at these positions is $\gtrsim 3$, which means that the observed flux requires an intrinsic unabsorbed flux that is 20 times greater. This is clearly impossible regardless of any uncertainties about the intrinsic line shape and the continuum level. To explain the observed flux, the ionizing intensity of the quasar as determined by our template spectrum from the observed continuum would have to be too low by a factor > 2. However, our full model, which accounts for the expected distribution of clumping and thus predicts greater transmission, naturally accounts for the observed flux with no change in the quasar spectrum.

Our conclusions are insensitive to the question of whether the H II region of the highest redshift quasar is surrounded by a region of neutral hydrogen (due to the fact that the universe had not been fully reionized by $z = 6.28$[27]) or not[28]; a distant neutral region would only add on the IGM damping wing[13] which produces a smooth, gradual suppression that should not alter the basic double-peak pattern. We note that the quasar may possess a velocity offset relative to Hubble flow due, for example, to a violent galactic merger that had originally activated the quasar. A 20Å shift at $z = 6.28$ would correspond to a velocity of 700 km s^{-1}; however, the close fit that we find between the predicted accretion shock position and the observed flux drop is evidence against the presence of a large velocity offset in the two quasars we have considered.

Our models provide the first direct evidence that two characteristic properties of quasars at low redshift are also applicable to bright quasars in the early universe. These properties include the quasar spectral template, which determines the ionizing intensity of the quasar, and the relation between black hole mass and halo velocity dispersion, which we have used to determine the host halo mass. Both observed spectra show a blue peak of about 75% of the height of the main ($\Delta\lambda > 0$) peak, and this is roughly matched by the models. However, if we were to increase the halo mass by an order of magnitude or increase the ionizing intensity by an order of magnitude, then we would predict a blue peak at least of equal height to the other peak. If, instead, we decreased the halo mass or the ionizing intensity by an order of magnitude then the resulting blue peak would be under 50% of the height of the main peak and the transmitted flux would decrease to zero already at $\Delta\lambda = -30$Å ($z = 4.795$) and $\Delta\lambda = -50$Å ($z = 6.28$), respectively. High-redshift quasars could in principle be much fainter intrinsically than they appear, if they are magnified by gravitational lensing[29,17]; our limits on the ionizing intensity, however, suggest that the two quasars we have modelled cannot be magnified by a factor $\gtrsim 10$.

We can also estimate from the data the total gas infall rates into these massive galaxies. The positions of the accretion shocks imply infall velocities of $\sim$ 400–500 km s^{-1} and shock radii of $\sim$ 80–90 kpc. Since gas at this radius is expected to have a density of $\sim$ 30 times the cosmic mean density[16], we obtain an accretion rate of $\sim 2000\, M_\odot$ yr^{-1}. At this rate, the host galaxies of these quasars could have been assembled in 3×10^8 yr, consistent with the 9×10^8 yr age of the universe at $z = 6.28$. Future comparison of our model to the *average* Lyα absorption profile of a statistical sample of bright, early quasars with similar luminosities and redshifts should allow us to fit the details of the absorption spectrum and refine our quantitative conclusions.

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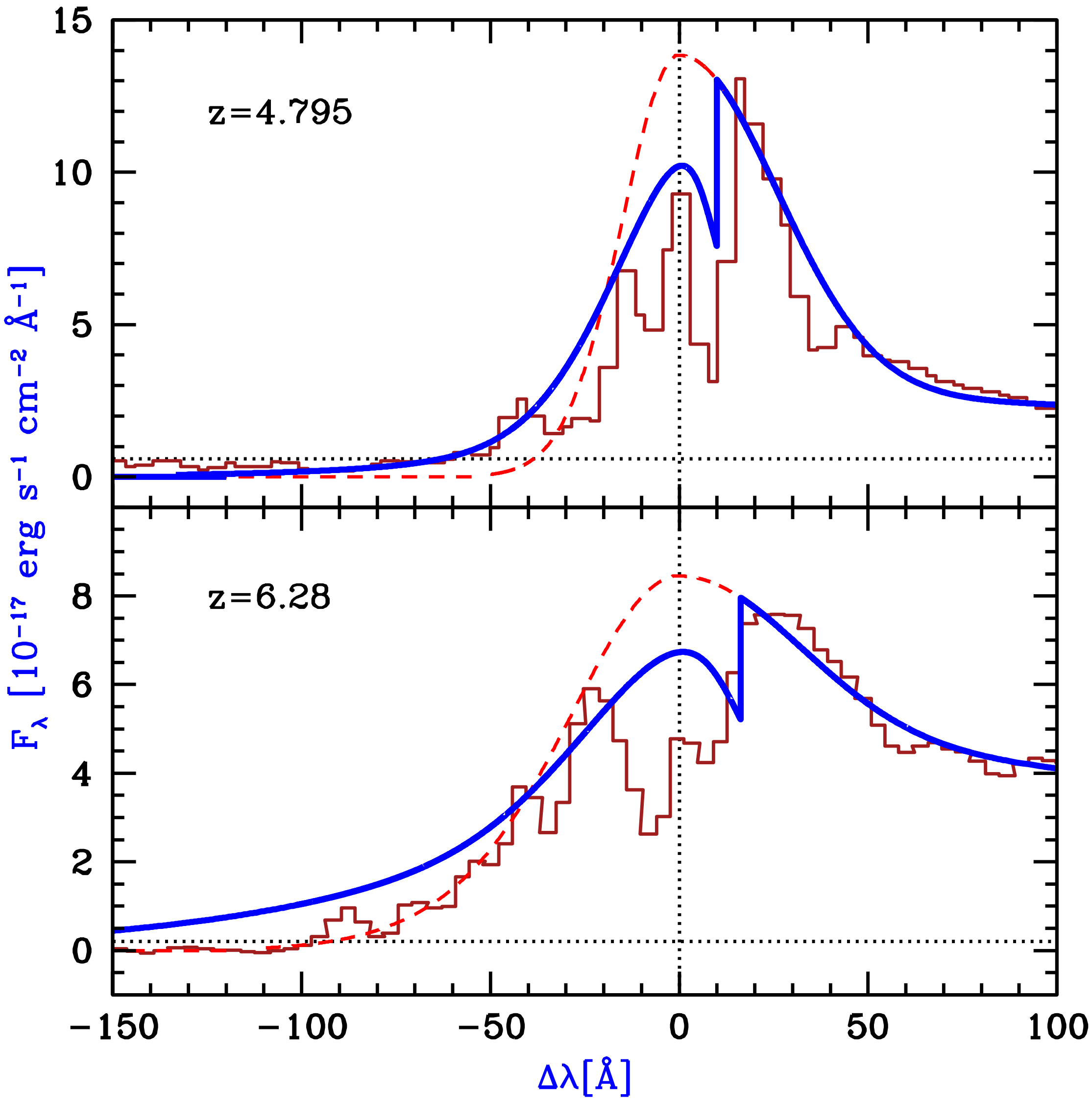

Fig. 1.— Comparison between models of cosmological infall and observed quasar spectra. The upper panel considers the redshift 4.795 ± 0.004 quasar SDSS 1122-0229[30]; based on the observed redshift and continuum level our model implies a $4.6 \times 10^8 M_\odot$ black hole residing in a $2.5 \times 10^{12} M_\odot$ host halo. The lower panel considers the redshift 6.28 ± 0.02 quasar SDSS 1030+0524[31], for which our model implies a $1.9 \times 10^9 M_\odot$ black hole residing in a $4.0 \times 10^{12} M_\odot$ host halo (we do not use a second spectral observation of this same source[32] since it appears to have a significantly lower signal-to-noise ratio). In each panel, the histogram shows the observed spectrum, the dashed line shows previous models that assume a uniform expanding universe, and the solid line shows our model which includes cosmological infall as well as a realistic distribution of gas clumps. Note that $\Delta\lambda$ is the observed wavelength measured relative to Lyα at the source redshift. In each panel, the vertical dotted line shows the position of the Lyα wavelength, and the horizontal dotted line shows the flux level of the highest transmission peaks seen in parts of the spectrum corresponding to the average intergalactic medium (i.e., at $\Delta\lambda \ll -150$Å). We assume an intrinsic emission line given by a sum of two Gaussian components, a form which best fits the line shape of most quasars at low redshift[33,34]; we fix the parameters for each quasar based on the unabsorbed part of the Lyα line at $\Delta\lambda > 20$. With this approach the models do not include any free parameters. Particular quasars are expected to show fluctuations around our predicted absorption profile, since we average over random lines of sight and density fluctuations. Throughout this paper we assume the standard cosmological parameters $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_b = 0.05$, $H_0 = 70$ km s^{-1} Mpc^{-1}, and $n = 1$.